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# Light Robotics: an all-optical nano- and micro-toolbox

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## ABSTRACT

Recently we proposed the concept of so-called Light Robotics including the new and disruptive 3D-fabricated micro-tools coined Wave-guided Optical Waveguides that can be real-time optically manipulated and remote-controlled with a joystick in a volume with six-degrees-of-freedom. Exploring the full potential of this new ‘drone-like’ light-driven micro-robotics in challenging microscopic geometries requires a versatile and real-time reconfigurable light addressing that can dynamically track a plurality of tiny micro-robots in 3D to ensure continuous optimal light coupling on the fly. Our latest developments in this new and exciting research area will be reviewed.

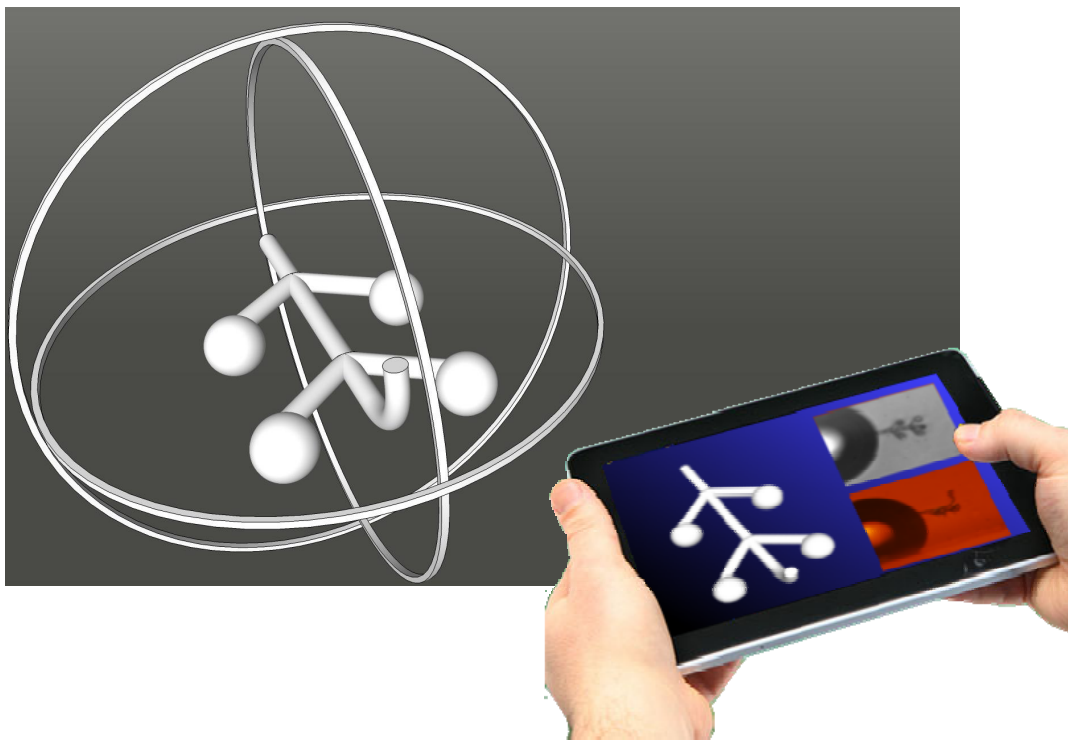
**Keywords:** light-driven micro-robotics, micro-fabrication, optical tracking, holography, Generalized Phase Contrast

## 1. INTRODUCTION

Just two years ago the Nobel Prize in Chemistry was celebrating the invention of so-called ‘optical nanoscopy’ that is comprised of a small family of highly advanced nanoscale light-based microscopy modalities that can all surpass the classical far-field diffraction limit and provide optical resolutions down to a few nanometers. Associated with these breakthroughs is the rapidly emerging field of pulsed-laser based 3D printing grounded on powerful approaches offered by e.g. nonlinear photopolymerizations. Currently, it is experimentally possible to 3D laser-print nanoscopic structures with voxel resolutions down to a few tens of nanometers. By adding a third key scientific accomplishment - namely the fascinating ability of focused light to capture, trap and manipulate tiny objects - one can approach a triangulation of new functionalities required for true light-driven nano-robotics. By integrating all these amazing optics and photonics breakthroughs we can create the conditions for

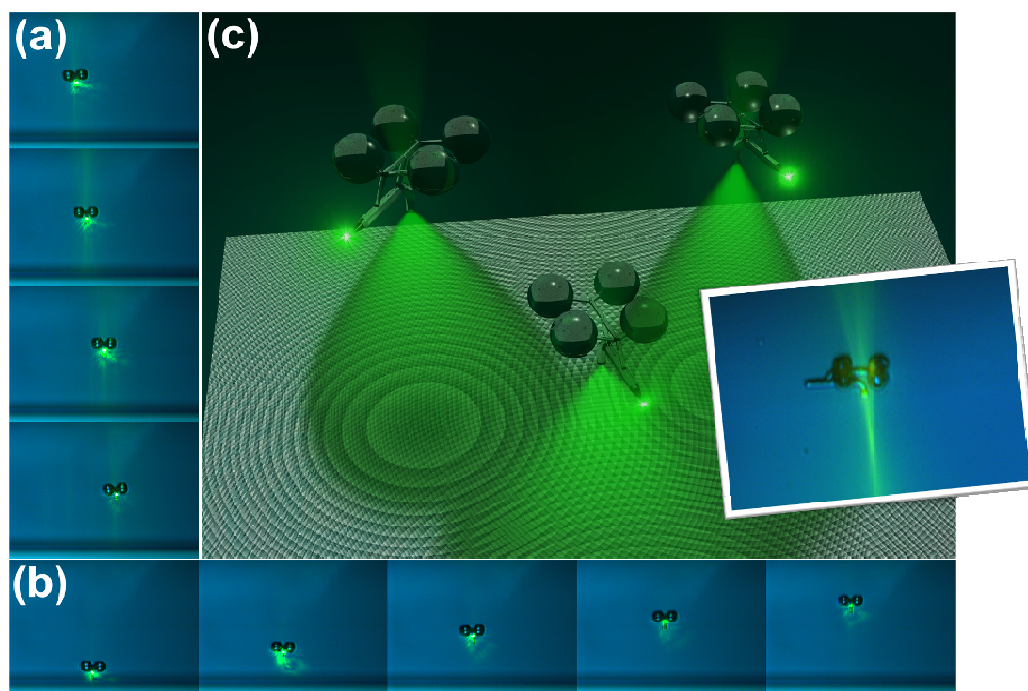
harnessing most of the functionalities required to unfold the fascinating concept of true so-called Light Robotics.

We are gradually beginning to see the many intriguing possibilities of directly equipping 3D laser-printed robotic micro-structures with advanced multi-functional nanoprobes or nanotips fabricated with true nanoscopic resolution. The uniqueness of such an approach is that even if a micro-biologist aims at exploring e.g. cell biology at nanoscopic scales, the main support of each laser-robotic structure can be 3D printed to have a size and shape that allows convenient laser manipulation in full 3D – even using relatively modest numerical aperture optics. An optical robot is typically equipped with a number of 3D printed "track-balls" that allow for real-time 3D light manipulation with six-degrees-of-freedom. This creates a drone-like functionality where each light-driven robot can be e.g. joystick-controlled and provide the user a feeling of stretching his/her hands directly into and interacting with the biologic micro-environment. The light-guided robots can thus act as free-floating probes to monitor micro-biologic processes and provide spatially targeted mechanical, chemical or even optical stimuli that would otherwise be impossible to achieve in a full 3D biologic environment.



**Fig. 1:** *Light Robotics in a nutshell*

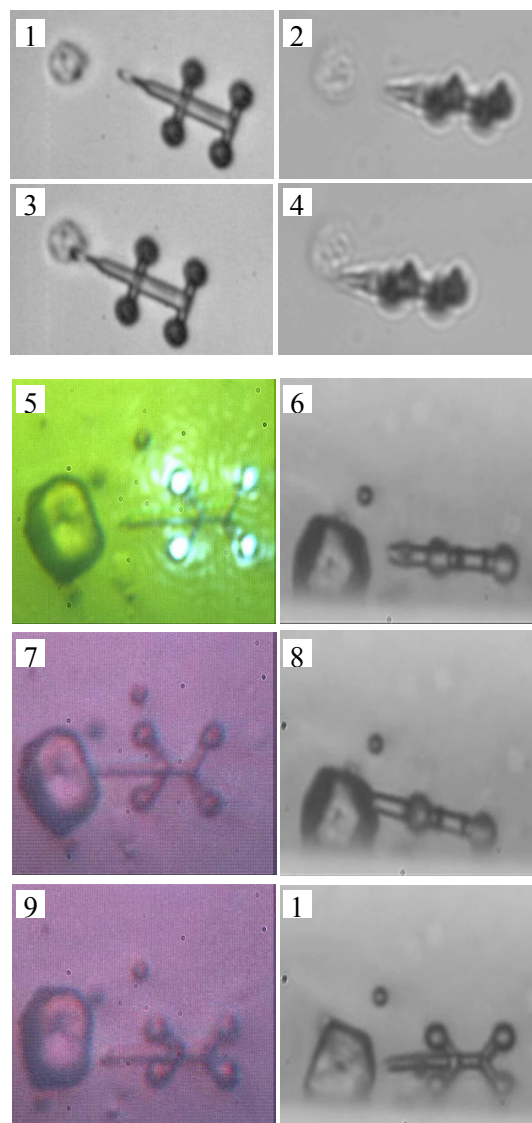
By harnessing the fascinating ability of focused coherent light to capture, trap and 3D-manipulate 3D-printed microscopic objects we are gradually approaching all the functionalities required for true light-driven micro-robotics. As Ashkin et al. showed in pioneering experiments at Bell Labs in the early 70es [1] and culminating with real optical tweezing demonstrations in the mid 80es, focused laser light is able to exchange momentum with small refractive particles and make them seek toward the laser-beam foci and thereafter stay stable with strongly reduced Brownian motions. In biological experiments, this takes best place in aqueous solutions in which living cells and other micro-organisms can be sustained and thrive in a relatively natural environment. Moreover, the liquid environment provides inherent cooling of the laser trapped particles and additional damping of Brownian fluctuations. As we all know, Ashkin's student Steven Chu continued this research work and refined it to the level where even atoms under special circumstances could be trapped and laser-manipulated i.e. the Nobel Prize in Physics in 1997. By cleverly combining and integrating all these amazing optics and photonics breakthroughs we can create the conditions for most of the functionalities required to develop functional light-driven micro-robotics [2-10]. An example of light-driven micro-robotics in action is graphically illustrated in Figure 1 above and Figure 2 below.



**Fig. 2:** Real-time 3D tracking of a plurality of 3D-printed light robots. Adapted from ref. [9].

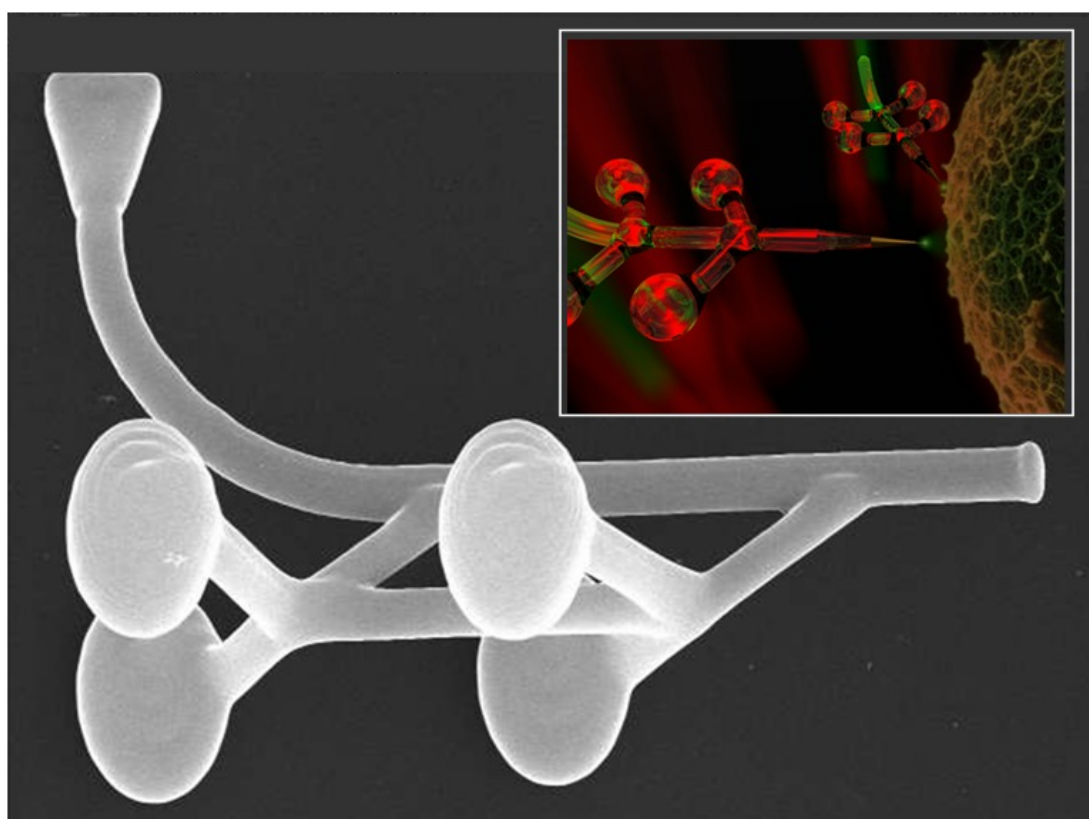
## 2. TOWARDS NANOPROBING ‘LIGHT ROBOTICS’

By exploring the aforementioned two-photon polymerization micro-fabrication, it is possible to equip 3D-printed optical micro-robotic structures with multi-functional biophotonic nanoprobes or nanotips fabricated with nanoscopic resolution. The uniqueness of such an approach is that even if a micro-biologist aims at exploring e.g. cell biology at nanoscopic scales, the main structure of each 3D-printed micro-robotic structure has a size and shape that allows convenient optical micro-manipulation in full 3D – even using relatively modest numerical aperture optics. Our earlier experimental examples are illustrated below – with simultaneous top and side-view imaging.



**Fig. 3:** (1)-(4) Light Robotic probing of a live T-cell imaged from top and side. (5)-(10) show an opto-mechanical probe-interaction with a tiny surface-positioned object. Adapted from refs. [3,4].

As can be seen in Figure 3 above each optical micro-robot is typically equipped with four 3D-printed "track-balls" that allow for real-time 3D light manipulation with six-degrees-of-freedom. This creates a drone-like functionality where each light-driven micro-robot can be e.g. joystick-controlled and provide the user a feeling of stretching his/her hands directly into and interacting with the biologic micro-environment. Light-guiding micro-robotic tools can be 3D-fabricated so that targeted and real-time coupled light [11-16] can be used as near-field irradiating and receiving nano-torches i.e. Figure 4 below.

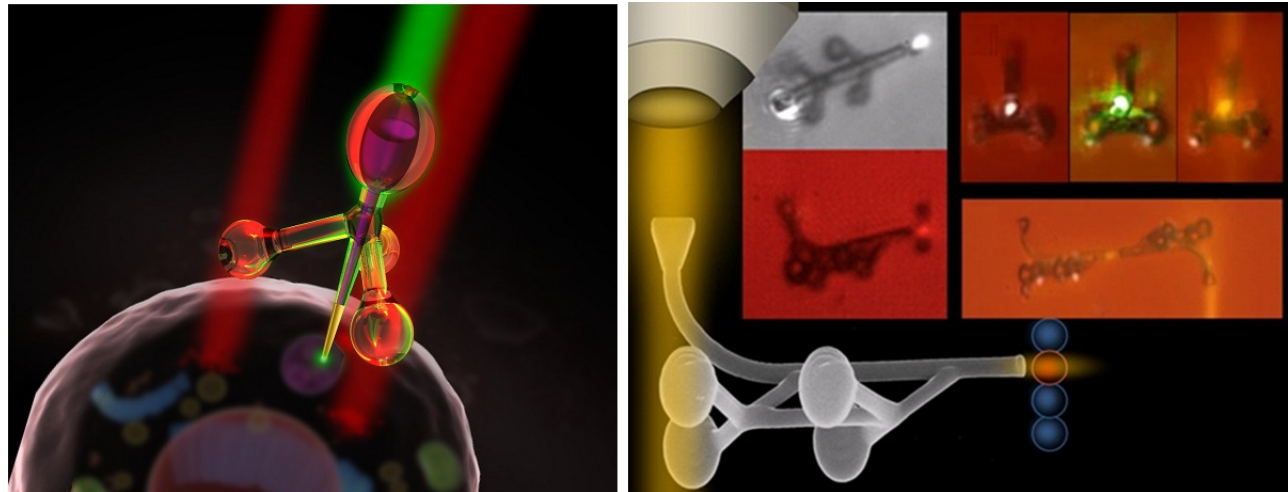


**Fig. 4:** *Light Robotic tool equipped with an integrated waveguide structure to act as an optical near-field probe for e.g. tip-enhanced Raman signal acquisition. Adapted from Ref. [8].*

The light-guided micro-robots can thus act as free-floating probes to monitor micro-biologic processes and provide spatially targeted mechanical, chemical or even optical stimuli that would otherwise be very difficult to achieve in a full 3D biologic environment. A single light robotic tool can e.g. be envisioned to perform measurement operations of receptors on a cell membrane and potentially even use the cell signaling network to initiate biochemical processes within the cell itself.

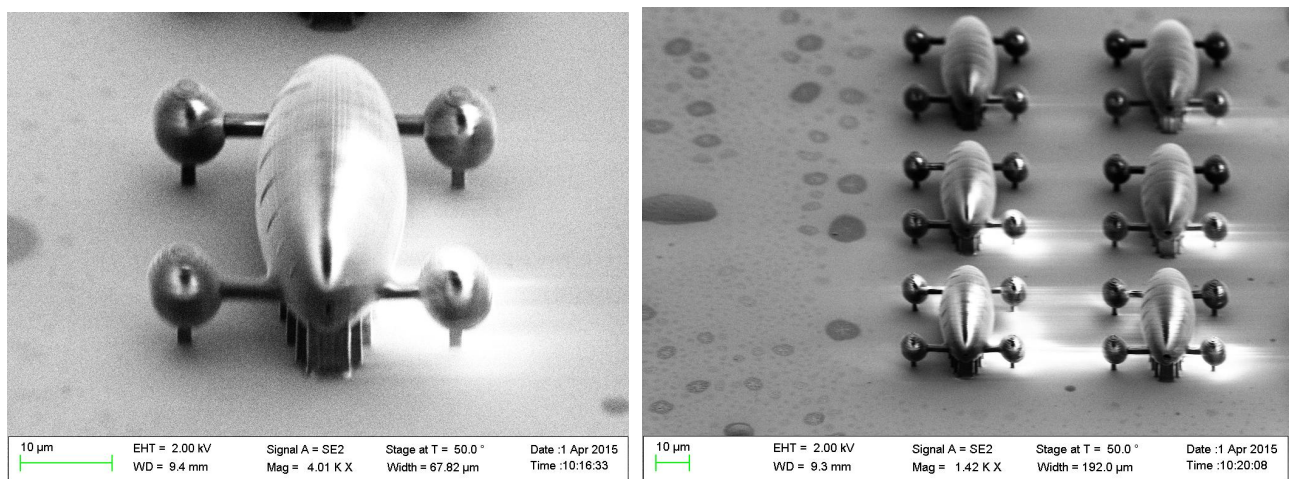


Moreover, light-programmed mechanical stimuli from the tools can be used to explore molecular effects that e.g. can convert mechanical signals picked up by cell membranes and converted to biochemical responses deeper within cells.



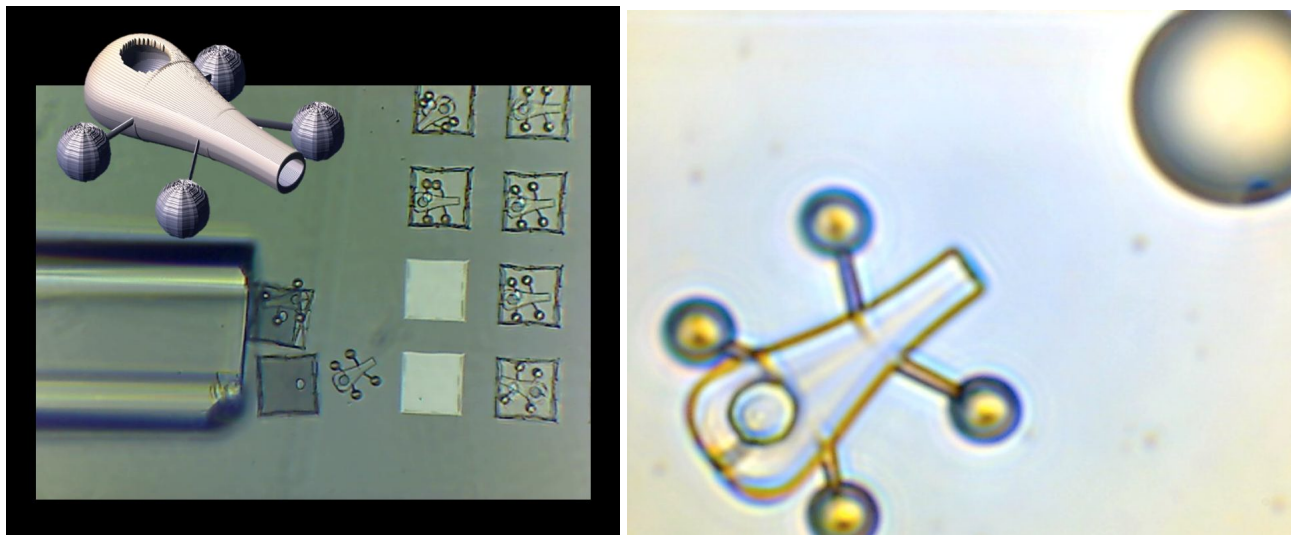
**Fig. 5:** *Light Robotics acting like an artificial virus. Right: experiments adapted from ref. X*

Figure 5 illustrates one of our future aims of fabricating and demonstrating the world's first artificial optical virus to perform a variety of light-actuated robotic functionalities on e.g. a living cell [17-20]. Preliminary test 3D-prints of such embodiments are SEM-imaged in Figure 6 below.



**Fig. 6:** *Hollow micro-body structures fabricated for cargo-delivering Light Robotics*

Our latest generation of light robotic tools are capable of material transport and incorporates a syringe action for loading and unloading a tiny cargo. The photoresist used in the fabrication of these light robots is practically transparent to the trapping beam wavelength and thus generates very little heat. On the other hand, metals are efficient energy-to-heat converters of light. Therefore, to enhance laser-induced heat generation in the polymerized light robots, we have embedded a thin metallic layer inside each of the light robots using vapor deposition. We have chosen a 1 nm titanium adhesion layer and a 5 nm gold layer deposited as a circular disk inside the body of each light robot.



*Fig. 7: Syringe-equipped light-driven micro-robotics. Adapted from ref. 20.*

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